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Near-IR spectroscopy of a young super-star cluster in NGC 6946: chemical abundances and abundance patterns ⋆

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ABSTRACT

Using the NIRSPEC spectrograph at Keck II, we have obtained H and K-band echelle spectra for a young ($\sim 10-15$ Myr), luminous ($M_V \sim -13.2$) super-star cluster in the nearby spiral galaxy NGC 6946. From spectral synthesis and equivalent width measurements we obtain for the first time accurate abundances and abundance patterns in an extragalactic super-star cluster. We find [Fe/H]$= -0.45 \pm 0.08$ dex, an average α-enhancement of $\approx +0.22 \pm 0.1$ dex, and a relatively low ^{12}C/^{13}C $\approx 8 \pm 2$ isotopic ratio. We also measure a velocity dispersion of $\approx$9.1 km/s, in agreement with previous estimates. We conclude that integrated high-dispersion spectroscopy of massive star clusters is a promising alternative to other methods for abundance analysis in extragalactic young stellar populations.

Key words: Galaxies: individual (NGC 6946), star clusters, abundances — infrared: galaxies — techniques: spectroscopic

1 INTRODUCTION

Star clusters have a long history as important tools for addressing a wide range of questions in astronomy. With few exceptions, they are "simple stellar populations" (SSPs), i.e. they are composed of stars born in a single burst and sharing the same chemical composition (at least to first order) and age. They have played an important role as test labs for models of stellar evolution (e.g. Maeder & Mermilliod 1981; Renzini & Fusi Pecci 1988; Chiosi et al. 1992). As confidence has grown in our ability to model their integrated properties, so has their importance as tracers of stellar populations in galaxies that are too distant for individual stars to be resolved.

The latter point is perhaps best illustrated by considering, for the moment, the old *globular clusters* (GCs) which are ubiquitous in all major galaxies. GCs typically contain large numbers of stars ($10^4 - 10^6$), so most phases of stellar evolution are well sampled and stochastic effects therefore minimized. Although there are still unsolved problems (e.g. concerning horizontal branch morphology), SSP models can now provide a reasonably realistic account of integrated GC observables such as broad-band colours and absorption line strengths as a function of age and metallicity. Thanks to the availability of efficient spectrographs on 8-10 m class telescopes, spectroscopy of GCs in galaxies well beyond the Local Group is now routinely feasible, and has been utilized in many studies to probe the stellar populations in early-type galaxies and constrain their ages and metallicities (e.g. Brodie & Strader 2006, and references therein). Much of this work has relied on measurements of absorption line features at relatively low ($\sim$ 10 Å) spectral resolution. In the optical, the Lick/IDS system of absorption line indices has found wide-spread use (Burstein et al. 1984; Trager et al. 1998), while indices for the near-infrared have been defined by Bica & Alloin (1987) and Vazdekis et al. (2003). Ages are typically estimated from Balmer line strengths (mainly Hδ, Hγ, and Hβ), with other indices being more sensitive to metallicity. However, detailed abundances of individual elements typically cannot be reliably measured at this resolution. In addition, the Lick/IDS system is not well tailored for studying young stellar populations, partly due to limitations in the empirical libraries used in the construction of SSP models, but also because the index definitions are designed primarily for studies of old stellar populations.

Until now, the main source of information about the chemical composition of *young* stellar populations beyond

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the Local Group has been measurements of emission lines in HII regions. However, these provide access to only a limited set of elements (mainly O, N, S) and often have to rely on empirical calibrations of line strengths vs. metallicity. The auroral lines (e.g. [OIII] 4363Å) are usually too faint to be measured directly, thus prohibiting a determination of the nebular temperature (Stasińska 2001). Furthermore, HII regions only offer a snapshot of the *present-day* chemistry and do not provide any information about the past history.

Spectroscopy of (massive) star clusters has the potential to provide information on the entire star formation histories of galaxies. For masses in the 10^5 M$_\odot$ – 10^6 M$_\odot$ range, star clusters typically have velocity dispersions of about 5–10 km/s, allowing studies of their integrated properties at spectral resolutions up to $\lambda/\Delta\lambda \approx 30{,}000$ or more. This is sufficient to constrain individual element abundances. However, extending this type of analysis to young clusters comes with its own set of difficulties. Compared to studies of old GCs, some of the main challenges are: 1) models for the massive stars found in clusters with ages of a few $\times 10^7$ years are much less certain than those of the low-mass stars found in old GCs (Massey & Olsen 2003) 2) the optical spectra are generally dominated by the relatively featureless spectra of hot stars, diluting absorption features and making them harder to measure, 3) for all but the most massive clusters, the integrated spectra may be dominated by a few massive stars, causing unpredictable stochastic fluctuations in integrated properties (e.g. Lançon & Mouhcine 2000).

In this letter we aim to take a first step towards deriving abundances for *young* extragalactic star clusters from their integrated light, by modelling the near-infrared spectrum of a luminous ($M_V = -13.2$) young ($\sim$ 10 Myr) star cluster in the nearby spiral galaxy NGC 6946. This object was first identified as a star cluster by Larsen & Richtler (1999) and was labelled NGC6946-1447 by them, but is located within a larger stellar complex first noted by Hodge (1967). Both $UBVI$ broad-band colours and spectroscopic observations of Balmer and He I absorption lines yield consistent age estimates in the range 10–15 Myr (Larsen et al. 2001; Efremov et al. 2002). From the luminosity and estimated age of the cluster, SSP models yielded a mass of $\sim 0.8{\times}10^6$ M$_\odot$ for a Salpeter-like IMF extending down to 0.1 M$_\odot$, or $\sim 0.55 \times 10^6$ M$_\odot$ if the IMF is log-normal below 0.4 M$_\odot$ (Larsen et al. 2001). A dynamical mass estimate, based on high-dispersion optical spectroscopy and HST imaging, yielded a somewhat higher mass of $\sim 1.7 \times 10^6$ M$_\odot$. Such massive clusters are sometimes called "super star clusters" (SSCs). Using isochrones from Girardi et al. (2000), we estimate that the cluster contains about 130 red supergiants. A detailed description of the cluster and surrounding stellar complex is given in Larsen et al. (2001, 2002).

No line emission is observed from the cluster itself but Efremov et al. (2002) estimated an oxygen abundance of $12 + \log(O/H) = 8.95 \pm 0.2$ from long-slit spectroscopy of nearby HII regions. Belley & Roy (1992) measured O abundances for HII regions distributed throughout the disk of NGC 6946 (using narrow-band imaging of O, N and H emission lines) and derived an oxygen abundance gradient of $\Delta\log(O/H)/\Delta R = -0.089 \pm 0.003\,\mathrm{dex\,kpc}^{-1}$ and a central value of $12+\log(O/H) = 9.37$. At the projected galactocentric distance of NGC6946-1447 (4.8 kpc), this corresponds to $12 + \log(O/H) = 8.94 \pm 0.01$. Kobulnicky et al. (1998) quote an O abundance of $12 + \log(O/H) = 9.13$ at a radius of 3 kpc, or $12 + \log(O/H) = 8.97$ at 4.8 kpc if we adopt the abundance gradient from Belley & Roy (1992). Thus, all available measurements consistently give $12 + \log(O/H)$ between 8.94 and 8.97, although the above O abundances are all based on measurements of the collisionally excited O lines vs. Balmer line ratios and may therefore be subject to systematic uncertainties at the 0.1-0.2 dex level.

2 OBSERVATIONS AND DATA REDUCTION

H and K-band high-resolution spectra were acquired on 13 July 2002, using the infrared spectrograph NIRSPEC (McLean et al. 1998) mounted at the Nasmyth focus of the Keck II telescope. The high resolution echelle mode, with a slit width of $0\farcs43$ (3 pixels) and a length of $12''$ was used, providing a spectral resolution of $\lambda/\Delta\lambda = 25,000$. The exposure times were 64 min and 48 min in the H and K bands, respectively, yielding a S/N of about 26 and 36 per pixel in the dispersion direction (the K magnitude of the cluster is about 13.0). The observations were obtained in pairs of exposures with a duration of 240 s each, nodded a few arcsec along the slit to allow reliable sky subtraction without any additional overhead for separate sky exposures. The NIRSPEC data has previously been used by Larsen et al. (2004) to derive a line-of-sight velocity dispersion of 8.8 ± 1.5 km/s for the cluster, in good agreement with the value of $10.0{\pm}2.7$ km/s derived by Larsen et al. (2001) (based on Keck/HIRES spectroscopy). We refer to Larsen et al. (2004) for details on the data reduction.

3 SPECTRAL ANALYSIS

Near-IR spectroscopy is a powerful tool to obtain accurate abundances of key metals in cool stars (T$_{\rm eff} \leq 5000$ K). Several atomic and molecular lines are strong and not affected by severe blending, making them powerful abundance tracers not only in stars but also in more distant stellar clusters and galaxies and for a wide range of metallicities and ages (Origlia et al. 1997; Oliva & Origlia 1998; Origlia et al. 2004). However, to properly account for line blending, abundance analysis from integrated spectra generally still requires full spectral synthesis techniques and not just equivalent width measurements of individual lines. Population synthesis may also be required to define the dominant contribution to the stellar luminosity.

The near IR stellar continuum of young stellar clusters and starburst galaxies is almost entirely due to luminous red supergiants (Origlia & Oliva 2000) and usually it dominates over nebular and dust emission. Based on the Girardi et al. isochrones, stars hotter than 10,000 K contribute only $\sim$ 5% of the H- and K-band flux at 15 Myrs. This represents a major, conceptual simplification in population and spectral synthesis techniques, making the interpretation of the integrated spectra much easier. The spectra can be modelled with an equivalent, average star, whose stellar parameters (temperature T$_{\rm eff}$, gravity log$g$ and microturbulence velocity ξ) mainly depend on the stellar age and metallicity. Both observations and evolutionary models (see e.g. Keller

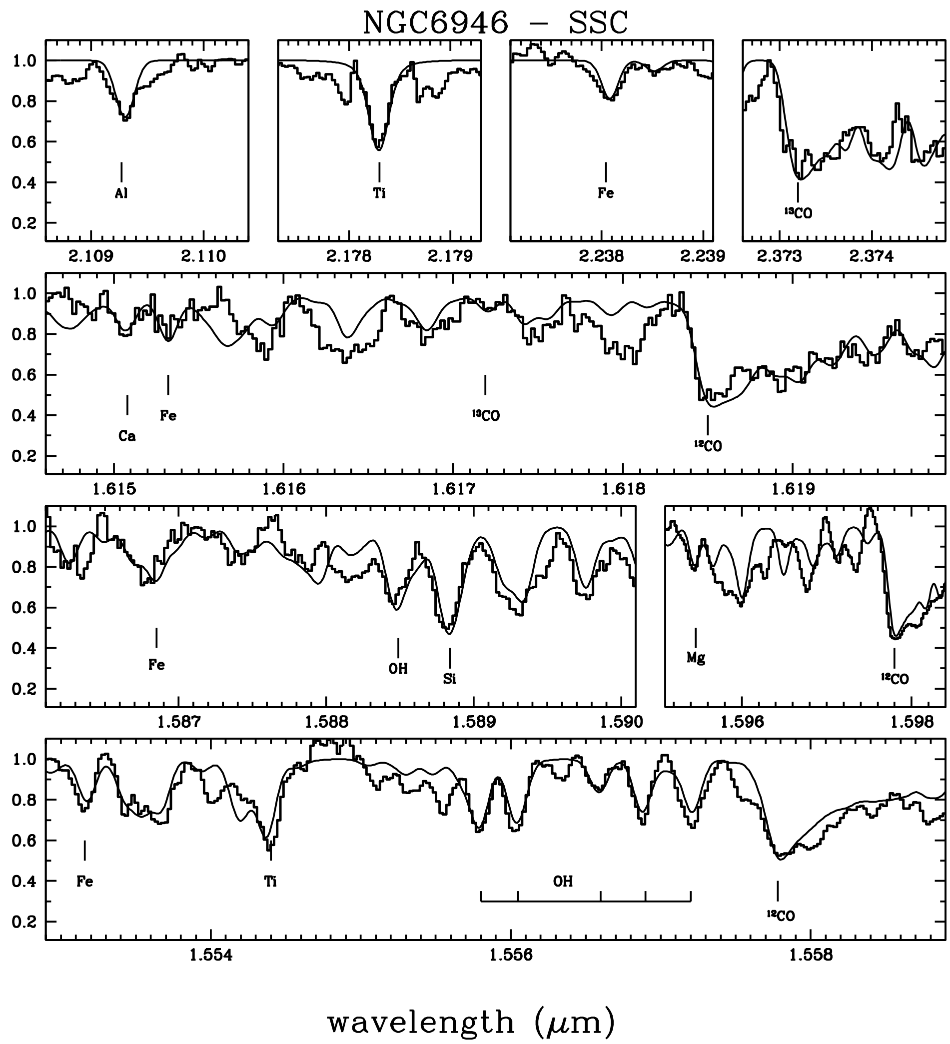

Figure 1. Near-IR spectra of the SSC of NGC 6946. Observed spectra: histograms; synthetic stellar best-fit solution: solid lines. A few atomic and molecular features of interest are also marked.

1999; Origlia et al. 1999; Massey & Olsen 2003, and references therein) suggest that red supergiants of ages between $\simeq$6 and 100 Myr and metallicities between 1/10 and Solar have low gravities (log g<1.0), low temperatures ($\leq$ 4000 K) and relatively high microturbulence velocity ($\xi \geq$3 km/s).

At the NIRSPEC resolution of R=25,000, several single roto-vibrational OH lines and CO bandheads can be measured and used to derive accurate oxygen and carbon abundances. Although our NIRSPEC setup was optimised for velocity dispersion measurements rather than abundance analysis, abundances of other metals can be derived from the atomic lines of Fe I, Mg I, Si I, Ti I, Ca I and Al I.

A grid of synthetic spectra of red supergiant stars for different input atmospheric parameters and abundances were computed, using an updated (Origlia, Rich & Castro 2002; Origlia et al. 2003) version of the code described in Origlia, Moorwood & Oliva (1993). Briefly, the code uses the LTE approximation and is based on molecular blanketed model atmospheres of Johnson, Bernat & Krupp (1980) at temperatures $\leq$4000 K and the ATLAS9 models for temperatures above 4000 K. Recently, the NextGen model atmospheres (Hauschildt et al. 1999) have been also implemented within the code and tested. Compared with the older models, the differences in the resulting abundances are only minor (well within a few hundredths dex; Rich & Origlia 2005). This is not surprising, since the major source of opacity in the near IR spectra of cool stars is H^- with a minimum around 1.6μm and small differences in the temperature structure of different model atmospheres have a minor impact on the overall abundance determination. The code also includes several thousands of near IR atomic lines and molecular roto-vibrational transitions due to CO, OH and CN. Three main compilations of atomic oscillator strengths are used, namely the Kurucz's database (c.f. *http://cfa-www.harward.edu/amdata/ampdata/kurucz23/sekur.html*), and those published by Bièmont & Grevesse (1973) and Meléndez & Barbuy (1999).

The code provides full spectral synthesis over the 1–2.5 μm range and abundance estimates are mainly obtained by best-fitting the full observed spectrum and by measuring the equivalent widths of a few selected features (Fig. 1), dominated by a specific chemical element, as a further cross-

Table 1. Adopted stellar atmosphere parameters and abundance estimates for the SSC in NGC 6946.

T_{eff} [K]	log g	ξ [km s^{-1}]	[Fe/H]	[O/Fe]	[Ca/Fe]	[Si/Fe]	[Mg/Fe]	[Ti/Fe]	[α/Fe][a]	[Al/Fe]	[C/Fe]
4000	0.5	3	-0.45 ±0.08	0.28 ±0.09	0.25 ±0.12	0.07 ±0.18	0.25 ±0.17	0.30 ±0.11	0.22 ±0.11	0.25 ±0.18	-0.25 ±0.11

[a] [α/Fe] is the average [$<$ Ca, Si, Mg, Ti $>$ /Fe] abundance ratio.

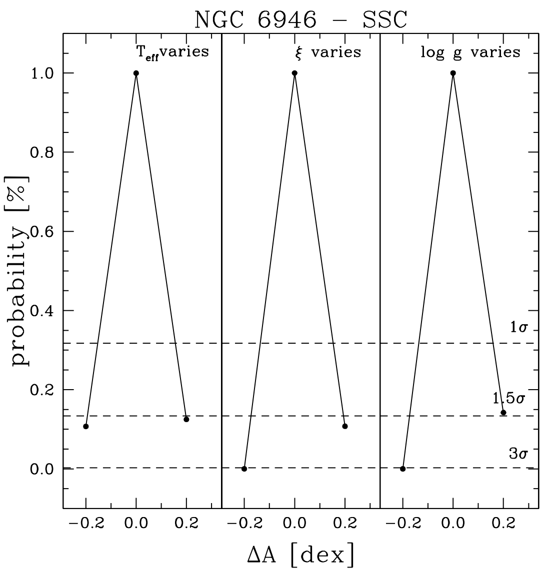

Figure 2. Average probability of a random realization of our best-fitting solution and the test models with varying temperature by $\Delta T_{\rm eff}$ of ±200K (left panels), microturbulence by $\Delta\xi$ of ∓1.0 km s^{-1} (right panels), and gravity by $\Delta log\ g$ of ±0.5 dex (middle panels), with respect to the best-fitting solution (see Sect. 3) for the SSC.

check. The equivalent widths were measured by performing a Gaussian fit with σ equal to the measured stellar velocity dispersion; typical values range between 100 and 500 mÅ with a conservative error of ±20 mÅ to also account for a ±2% uncertainty in the continuum positioning. By best-fitting the full observed IR spectrum and by measuring the equivalent widths of selected lines, we obtained the following stellar parameters and abundance patterns: $T_{\rm eff}$=4000, log$g$=0.5, ξ=3, [Fe/H]=–0.45; [O/Fe]=+0.28, [<Si,Mg,Ca,Ti>/Fe]=+0.22; [Al/Fe]=+0.25; [C/Fe]=–0.25. We also measure ^{12}C/^{13}C $\approx 8 \pm 2$.

Table 1 lists the derived abundances and their associated random errors at 90% confidence. Reference Solar abundances are from Grevesse & Sauval (1998). In addition, we also measure a heliocentric radial velocity of $< v_r >=$ $+141 \pm 2$ km/s and velocity dispersion (corrected for instrumental broadening) of $\approx 9.1 \pm 1$ km/s. These numbers agree reassuringly well with previous estimates (Efremov et al. 2002; Larsen et al. 2001, 2004).

3.1 Error budget

Synthetic spectra with lower element abundances are *systematically* shallower (have weaker features) than the best-fit solution, while the opposite occurs when higher abundances are adopted. In order to check the statistical significance of our best-fit solution, as a function of merit we adopt the difference between the model and the observed spectrum (hereafter δ). This parameter is more effective for quantifying systematic discrepancies than the classical χ^2 test, which is equally sensitive to *random* and *systematic* scatters (see Origlia et al. 2003, for more details).

Since δ is expected to follow a Gaussian distribution, we compute $\overline{\delta}$ and the corresponding standard deviation (σ) for the best-fit solution and 6 *test models* with stellar parameters varying by $\Delta T_{\rm eff}$±200 K, Δlog g=±0.5 and $\Delta\xi$∓1.0 km s^{-1} with respect to the best-fit, and abundances varying accordingly by $\approx \pm 0.2$ dex, in order to still reproduce the depth of the observed features. We then extract 10000 random subsamples from each *test model* (assuming a Gaussian distribution) and we compute the probability P that a random realization of the data-points around a *test model* display a $\overline{\delta}$ that is compatible with the *best-fit* model. $P \simeq 1$ indicates that the model is a good representation of the observed spectrum.

The left panel of Fig. 2 shows the results for the observed H band spectrum of the SSC in NGC 6946. It can be easily appreciated that the best-fit solution provides in all cases a clear maximum in P (>99%) with respect to the *test models*, which are statistical significant only at $> 1.5\sigma$ level. We also computed test models with the same stellar parameters as the best-fit solution and varying only the abundances. Models with ±0.1 dex with respect to the best-fit solution are significant at $1 - 1.5\sigma$ level, while models with ±0.2 dex are only marginally acceptable at a $> 3\sigma$ level.

Hence, as a conservative estimate of the systematic error in the derived best-fit abundances, due to the residual uncertainty in the adopted stellar parameters, one can assume a value of $\approx \pm 0.1$ dex. Moreover, since the stellar features under consideration show a similar trend with variation in the stellar parameters, although with different sensitivity, *relative* abundances are less dependent on stellar parameter assumptions, reducing the systematic uncertainty to <0.1 dex.

4 DISCUSSION AND CONCLUSIONS

Based on near-infrared H and K-band spectroscopy, we have carried out a detailed abundance analysis of a young massive star cluster in the nearby spiral galaxy NGC 6946. In this exploratory work, we have derived abundances of several individual key elements, including Fe, Ca, Si, Mg and Ti. We find a sub-solar Fe abundance ([Fe/H] $= -0.45 \pm 0.08$), while the α-element to Fe abundance ratios are all enhanced with respect to the Solar values with a mean [α/Fe] $=$ 0.22 ± 0.11. The O abundance derived from the cluster spectrum is [O/H]$= -0.17 \pm 0.09$, about 0.3 dex lower than the value based on HII regions at the same galactocentric dis-

tance. We find a $^{12}C/^{13}C$ ratio of $\approx 8 \pm 2$, similar to or slightly lower than typically observed in red supergiants in Galactic open clusters (Luck 1994; Gonzalez & Wallerstein 2000) and in the (more metal-poor) cluster NGC 330 in the SMC (Gonzalez & Wallerstein 1999). Standard stellar models (Schaller et al. 1992) predict a surface $^{12}C/^{13}C$ ratio of ~ 17 for a 15 $M_{\odot}$, ~ 12 Myr-old (Solar metallicity) red supergiant, about a factor of two higher than the value derived here.

Super-solar [α/Fe] ratios are usually interpreted as signatures of rapid, bursty star formation, with the gas mainly enriched by Type II supernovae with short-lived, massive progenitor stars (McWilliam 1997). Stellar populations formed over timescales of several Gyrs or more are expected to show solar-like α/Fe-element abundance ratios, as observed in the Milky Way thin disk.

In this context, it is worth noting that the complex hosting NGC6946-1447 may qualify as a 'localized starburst' (Efremov 2004). Timing is a critical issue, however: in order to produce super-solar [α/Fe] ratios, the starburst must have *preceded* the formation of the cluster itself by several Myrs. The delay must have been long enough for Type II SNe to produce significant amounts of α-elements, and enough time must then have elapsed to allow mixing of the pre-existing gas with α-enhanced ejecta before the cluster formed. Interestingly, reconstruction of the field star colour-magnitude diagram has provided some evidence for star formation in the complex at least 10–15 Myr prior to the formation of the cluster (Larsen et al. 2002). Alternatively, the current global SFR in NGC 6946 may be sufficiently elevated above the past average to cause a general enrichment of the ISM with α-elements. Addressing these questions more quantitatively would require a detailed modeling of the chemical enrichment history and a knowledge of the past star formation history which is currently not available.

This study represents one of the first cases of a detailed abundance analysis of a star-forming galaxy beyond the Local Group. While many uncertainties remain, we suggest that observations of extragalactic young star clusters hold great potential for constraining the chemical enrichment histories of their parent galaxies.

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